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On Wave Processes in the Solar Atmosphere

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SUMMARY OF COMPLETED WORK

I. Solar Physics

New calculations of the acoustic wave energy fluxes generated in the solar convective zone have been performed by Dr. Z. Musielak in collaboration with Drs. R. Rosner (University of Chicago), R. Stein (Michigan State University), and P. Gail and P. Ulmschneider (University of Heidelberg). The original theory developed by Lighthill in 1952 was then modified by Stein in 1967. The treatment of convective turbulence in the sun and solar-like stars, in particular, the precise nature of the turbulent power spectrum has been recognized to be one the most important issues in the wave generation problem. In all papers that followed the Lighthill-Stein theory of sound generation, the turbulence (which is assumed to be the only source of the generated waves) has been described by an *ad hoc* turbulent energy spectrum which is assumed to be factorized into a frequency-independent (spatial) spectrum and a frequency-dependent (temporal) spectrum; the latter is often referred to as the "frequency factor". Several different functional forms for the spatial and temporal spectra have been considered in the literature and differences between the energy fluxes obtained for different forms of the spectrum often **exceed two orders of magnitude.** The basic criterion for choosing the appropriate spectrum was the maximal efficiency of the wave generation. We have used a different approach based on physical and empirical arguments as well as on some results from numerical simulations of turbulent convection. The simulations carried out by Drs. Cattaneo and Malagoli helped us to establish a physically meaningful description of the spatial and temporal turbulent energy spectra, as well as to provide a useful database to calibrate the acoustic models. In our recent work, we have incorporated the spectra in a newly corrected version of the Lighthill-Stein theory of acoustic wave generation. We have used this new approach to calculate the acoustic wave energy fluxes generated in the solar convective zone and found that the obtained *total acoustic wave energy flux does not depend sensitively on the details of the turbulent energy* *spectrum.* Instead, the flux is sensitive to the solar convective zone model which, in our calculations, is based on the mixing-length theory and its parameter α. For $\alpha = 1$, the calculated acoustic wave energy flux for the Sun is roughly one order of magnitude lower than that previously obtained. However, if α is increased to 2, the obtained flux is of the order of $10^8\ erg/cm^2 s$ which may represent a sufficient amount of energy for chromospheric heating. A paper containing these results and a new version of the Lighthill-Stein theory was published in *The Astrophysical Journal* in March 1994. The obtained results are important in solving the longstanding problem of solar physics, namely, what is the role of the acoustic wave energy in the heating of the solar atmosphere and in the excitation of the solar p-mode oscillations.

In our research supported by this NASA grant we have also considered the excitation of magnetic flux tube waves which can carry energy along the tubes far away from the region of their origin. We have revised and improved our treatement of generation of these waves and calculated the tube wave energy fluxes for the Sun. The obtained results indicate that the magnetic tube wave energy fluxes may contribute significantly to the energy balance in the lower part of the solar chromosphere and may be especially important in heating of the chromospheric network. One paper on this subject was published in *The Astrophysical Journal* in August 1995, another paper is submitted to the same journal.

In order to understand transfer of the wave energy originated in the solar convective zone to the outer atmospheric layers, one has to compute wave propagation and dissipation in highly nonhomogeneous solar atmosphere. This sort of calculations usually requires time-dependent and nonlinear codes. P. Ulmschneider and Z. Musielak have calculated the propagation of nonlinear magnetic tube waves in the solar atmosphere and studied mode coupling, shock formation and heating of the local medium. In a paper recently published in *Astronomy and Astrophysics* we showed that these waves may indeed efficiently heat the solar atmosphere and that the heating will be especially significant in the chromospheric network (see Huang, Musielak and Ulmschneider 1995).

The propagation of waves in the solar outer atmospheric layers is also important for explaining the observed spectrum of the solar p-mode oscillations. Drs. Z. Musielak and R. Moore (NASA/MSFC) have been working on the wave trapping problems and on evaluation of critical frequencies for wave reflection in the solar atmosphere. One paper on this subject will appear in *The Astrophysical Journal* in November 1995, and two other papers are in preparation. The problem of the observed short period tail for the p-mode spectrum is likely to be explained by using these results.

The fact that the solar wind is originated in solar coronal holes has been well-known for many years, however, the mechanism for acceleration of the wind from these holes is still unknown. Also, it is unclear what is the main physical mechanism responsible for heating of the coronal holes. Recent work done by Drs. Z. Musielak (UAH), Krogulec (Uni. Gdansk), R. Moore and S. Suess (NASA/MSFC) and R. Rosner (Uni. Chicago) has shown that the role played by Alfven waves in the wind acceleration and the coronal hole heating is dominant. The results of these calculations were published in *The Astrophysical Journal Letters* and in *Journal of Geophysical Research.* In addition, the authors indicate that the main source of these waves for the heating and the wind acceleration are very likely solar microflares extensively observed in the UVSP data. New extensive studies of the physical processes responsible for the solar wind acceleration are being undertaken as a result of this support. First obtained results will be submitted for publication in *The Journal of Geophysical Research.* We are presently working on construction of self-consistent models of the solar coronal wind based on the reflected Alfven waves.

The results discussed above have been obtained for the Sun. Presently, we are performing calculations of wave energy fluxes generated in late-type dwarfs stars and studying physical processes responsible for the heating of stellar chromospheres and coronae. This will allow us to investigate solar-stellar connections.

II. Physics of Waves

The second part of our project concerning investigation of wave propagation in highly inhomogeneous stellar atmospheres has been explored in detail. Our approach is based on a new analytical tool developed by Musielak. Fontenla nd Moore (1992) who showed how to calculate the wave critical frequency and to estimate the height in stellar atmospheres at which reflection becomes dominant. In addition, a new approach based on Dirac equations has been developed to investigate coupling between different MHD waves propagating in stratified stellar atmospheres (Alicki, Musielak, Sikorski and Makowiec, 1994). Presently, we are working on extending these results to acoustic and magnetic tube wave propagation and applying them to late-type dwarfs. At the same time, we have begun developing a numerical code to study non-WKB linear and nonlinear MHD waves and we are now performing extensive tests of this numerical tool. Our recent results will be published in *The Astrophysical Journal* in November 1995.

Refereed Publications Resulting From This Support

"On Sound Generation by Turbulent Convection: A New Look at Old Results"
Musielak, Z. E., Rosner, R., Stein. R. F., Ulmschneider, P., *Astrophys. J.*, **423**, 474-487 (1994).

"On Dirac Equations for Linear Magnetoacoustic Waves Propagating in and Isothermal Atmosphere"
Alicki, R., Musielak, Z. E., Sikorski. J., and Makowiec, D. *Astrophys. J.*, **425**, 919-926 (1994).

"On Reflection of Alfven Waves in the Solar Wind"
Krogulec, M., Musielak, Z. E., Suess, S. T. and Nerney, S. F. *J. Geophys. Res.* (1994) - in press.

"On the Origin of "Dividing Lines" for Late-Type Giants and Supergiants"
Rosner, R., Musielak, Z. E., Cattaneo, F., Moore, R. L., and Suess, S. T., *Astrophys. J. Letters*, **442**, L25-L28 (1995).

"On the Excitation of Nonlinear Magnetic Tube Waves Waves in the Solar Atmosphere"
Huang, P., Musielak, Z. E., and Ulmschneider, P. *Astron. Astrophys.* **297**, 579-587 (1995).

"On the Generation of Flux Tube Waves in Stellar Convection Zones. II. Improved Treatement of Longitudinal Tube Wave Generation"
Musielak, Z. E., Rosner, R., Gail, H. P. and Ulmschneider, P., *Astrophys. J.*, **448**865 (1995).

"Klein-Gordon Equation and the Local Critical Frequency for Alfven Waves Propagating in an Isothermal Atmosphere"
Musielak, Z. E. and R. L. Moore, *Astrophys. J.*, **451**, in press (1995).

"Numerical Studies of MHD Body and Surface Waves: Single Magnetic Interface and Magnetic Slab"
Wu, S. T., Xiao, Y. C., Musielak, Z. E., and Suess, S. T., *Solar Phys.*, in press (1994).

"Reflection Coefficient and Tunneling Effects for Alfven Waves Propagating in the Solar Wind"
Krogulec, M., Musielak, Z. E., and Suess, S. T., *Astron. Astrophys.*, submitted (1995).

"On the Generation of Flux Tube Waves in Stellar Convection Zones. III. Transverse Tube Waves Driven by Forced Turbulence"
Musielak, Z. E., Rosner, R., Gail, P. H., Ulmschneider, P., and Hunag, P. *Astrophys. J.* submitted (1995).

Non-Referred Papers Resulting From This Support

"Alfven Wave Resonances and Flow Induced by Non-Linear Alfven Waves in a Stratified Atmosphere"
Stark, B. A., Musielak, Z. E. and Suess, S. T.
Solar Wind Eight, in press (1995).

"Generation of Linear and Nonlinear Magnetic Tube Waves in the Solar Atmosphere"
Musielak, Z. E., Rosner, R. and Ulmschneider, P.
IAU Colloquium No. 153 on *Magnetodynamic Phenomena in the Solar Atmosphere*,
Eds. Y. Uchida, T. Kosugi and H. S. Hudson, in press (1995).

Presentations Resulting From This Support

"The Role of Alfven Waves in Solar Wind Acceleration"
Krogulec, M., Musielak, Z. E., Suess, S. T., Nerney, S. F. and Moore, R. L.
AAS Meeting, Tucson AZ, January 1995.
Bulletin of AAS, **26**, 1472 (1994).

"Klein-Gordon Equation and Reflection of Alfven Waves"
Musielak, Z. E. and Moore, R. L.
AAS Meeting, Tucson AZ, January 1995.
Bulletin of AAS, **26**, 1520 (1994).

"Generation of Linear and Nonlinear Magnetic Tube Waves in the Solar Atmosphere"
Musielak, Z. E., Rosner, R. and Ulmschneider, P.
IAU Colloquium No. 153 on *Magnetodynamic Phenomena in the Solar Atmosphere*,
Makuhari near Tokyo, Japan, May 1995.

"Propagating Alfven Waves, Intermittent Magnetic Levitation, and Coronal Heating in Coronal Holes"
Moore, R. L., Musielak, Z. E., Krogulec, M. and Suess, S. T.
SPD Meeting, Memphis TN, June 1995.
Bulletin of AAS, **27**, 975 (1995).

"Klein-Gordon Equation and Reflection of Alfven Waves"
Musielak, Z. E. and Moore, R. L.
SPD Meeting, Memphis TN, June 1995.
Bulletin of AAS, **27**, 975 (1995).

"Klein-Gordon Equations for Acoustic Waves and Their Applications in Helioseismology"

Neergaard, L. F., Musielak, Z. E. and Hathaway, D. H.
SPD Meeting, Memphis TN, June 1995.
Bulletin of AAS, **27**, 954 (1995).

"Self-Consistent Models of the Solar Wind Accelerated by Alfven Waves"
Ong, K. K., Krogulec, M. and Musielak, Z. E.
SPD Meeting, Memphis TN, June 1995.
Bulletin of AAS, **27**, 973 (1995).

"Alfven Wave Resonances and Flow Induced by Non-Linear Alfven Waves in a Stratified Atmosphere"
Stark, B. A., Musielak, Z. E. and Suess, S. T.
Solar Wind Eight, Santa Rosa CA, June 1995.